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Report Title

Noninvasive assessment of attention state from correlated oscillations in brain and muscle

ABSTRACT

In motor task, correlated oscillations are found between the brain (motor cortex electroencephalogram, EEG) and muscle (electromyogram, EMG) activity in the beta band (15-30 Hz) frequency range (EEG-EMG coherence), but the functional role of which is unidentified. The aim of the project was to test if EEG-EMG coherence during a motor task is influenced by the amount of attention to the motor task. EEG-EMG coherence between motor tasks with different levels of attention was examined in healthy young adults. The task included steady finger force production to a target with a right hand. The level of attention to the task was objectively modified by progressively varying the visual feedback condition of the task performance. EEG-EMG coherence increased with the increases in the visual feedback gain and was greatest when subjects paid attention to the task without receiving visual feedback of their performance. There was no significant correlation between the subjective VAS score and EEG-EMG coherence in the individual data. The greater beta-band EEG-EMG coherence with increased visual feedback gain supported that correlated oscillations in brain and muscle in the beta band have a potential for objectively detecting the attention status that may not be detected from subjective reports.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Number of Papers published in peer-reviewed journals: 0.00

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Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

(d) Manuscripts

Number of Manuscripts: 0.00

Patents Submitted

Patents Awarded

Awards

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
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FTE Equivalent:

Total Number:

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
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FTE Equivalent:

Total Number:

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
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Lewis A. Wheaton	0.05	No
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Minoru Shinohara	0.22	No
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FTE Equivalent:	0.27	
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Total Number:	2	
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Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
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FTE Equivalent:

Total Number:

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

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Names of Personnel receiving masters degrees

<u>NAME</u>
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Names of personnel receiving PHDs

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Names of other research staff

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Sub Contractors (DD882)

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Final STIR Report

Noninvasive assessment of attention state from
correlated oscillations in brain and muscle

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ABSTRACT

In motor task, correlated oscillations are found between the brain (motor cortex electroencephalogram, EEG) and muscle (electromyogram, EMG) activity in the beta band (15-30 Hz) frequency range (EEG-EMG coherence), but the functional role of which is unidentified. The aim of the project was to test if EEG-EMG coherence during a motor task is influenced by the amount of attention to the motor task. EEG-EMG coherence between motor tasks with different levels of attention was examined in healthy young adults. The task included steady finger force production to a target with a right hand. The level of attention to the task was objectively modified by progressively varying the visual feedback condition of the task performance. EEG-EMG coherence increased with the increases in the visual feedback gain and was greatest when subjects paid attention to the task without receiving visual feedback of their performance. There was no significant correlation between the subjective VAS score and EEG-EMG coherence in the individual data. The greater beta-band EEG-EMG coherence with increased visual feedback gain supported that correlated oscillations in brain and muscle in the beta band have a potential for objectively detecting the attention status that may not be detected from subjective reports.

STATEMENT OF THE PROBLEM

The attention state may change with environment, fatigue, and training. On the battlefield, war-fighters are required to pay attention to the shooting target while watching their surroundings to avoid an attack. Severe environmental, physical, and psychological conditions (*e.g.*, heat, cold, stress, fatigue, and lack of sleep/rest) may hinder the war-fighters' ability to pay full attention to the main task or target. The performance of the main motor task in these conditions will be influenced by the individual's attention to it. The problem is it is very difficult to assess objectively and quantitatively. The aim of the project was to test if EEG-EMG coherence during a motor task is influenced by the amount of required attention to the motor task. The project is relevant to the research area of "8.4 Neurophysiology and Cognitive Neuroscience (8. Life Sciences)" in the Army Research Office.

SUMMARY OF THE MOST IMPORTANT RESULTS

EEG-EMG coherence increased with the increases in the visual feedback gain and was greatest when subjects paid attention to the task without receiving visual feedback of their performance. There was no significant correlation between the subjectively determined VAS score and EEG-EMG coherence in the individual data.

CONCLUSIONS

The greater beta-band EEG-EMG coherence with increased visual feedback gain supported that correlated oscillations in brain and muscle in the beta band have a potential for objectively detecting the attention status that may not be detected from subjective reports. Future studies are warranted that will extend these findings to other muscles, task conditions, and subject populations.

1. BACKGROUND

Optimal human movement performance is achieved when the individual is focused on the specific task with full attention. The attention state may change with environment, fatigue, and training. On the battlefield, war-fighters are required to pay attention to the shooting target while watching their surroundings to avoid an attack. Severe environmental, physical, and psychological conditions (*e.g.*, heat, cold, stress, fatigue, and lack of sleep/rest) may hinder the war-fighters' ability to pay full attention to the main task or target. The performance of the main motor task in these conditions will be influenced by the individual's attention to it, which is very difficult to assess objectively and quantitatively.

Motor tasks involve the activation of muscle by the brain. Electrical activity of the brain and muscle may be obtained as an electroencephalogram (EEG) from the motor cortex and as an electromyogram (EMG) from the activated muscle, respectively (Fig. 1). EEG electrodes on the scalp measure activity from a large number of neurons in underlying regions of the brain. Each neuron generates a small electrical field that changes over time. The source of current causing the fluctuating scalp potential is primarily the pyramidal neurons and their synaptic connections to deeper layers of the cortex. The oscillations are a result of the reciprocal interaction of excitatory and inhibitory neurons in circuit loops. EEG rhythms depend in part on activity in the thalamus. EMG is a composite of muscle fiber action potentials occurring in the muscle. The action potentials occur at somewhat random intervals, thus the EMG signal may be positive or negative. The EMG signal is often rectified to extract the essential information.

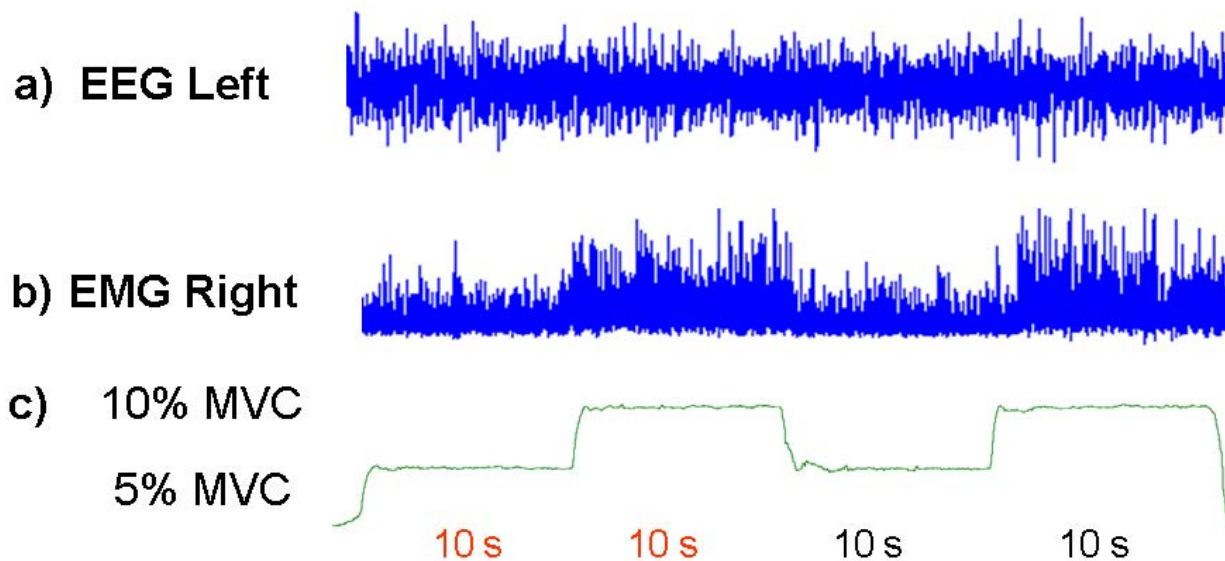


Figure 1. Example for EEG (from motor cortex) and EMG (from a hand muscle, rectified) recordings when the index finger produced 5% and 10% of maximal force.

The coherence between cortical and muscular activity was originally studied by investigating the coherence between EMG and magnetoencephalogram (MEG). MEG measures the magnetic fields generated by the electrical activity in the brain. Based on Maxwell's equations, any electrical current will produce an orthogonally oriented magnetic field. MEG measures this field to find the locations of the neuronal sources in the brain. In comparison to EEG, MEG has good spatial and temporal resolution but it is very expensive. Halliday concluded that the use of EEG to investigate functional aspects of cortical activity during voluntary movement in humans is comparable to the use of MEG (Halliday et al. 1998). Coherence analysis of EEG and EMG during repeated periods of maintained wrist extension and flexion, showed correlation in the beta band that matched previously observed results. Thus, the proposed research will employ EEG-EMG analysis.

In this study, we were interested in the correlated oscillations between the brain (EEG) and muscle (EMG) activity in the beta band (15-30 Hz) frequency range (EEG-EMG coherence, Fig. 2 as an example) (Halliday et al. 1998; Kilner et al. 1999; Mima and Hallett 1999), the functional role of which is unidentified. Corticomuscular coherence in the beta band is regarded to arise from the oscillatory synchronous discharge of populations of corticospinal cells around 15-30 Hz (Baker et al. 1997). Since EEG-EMG coherence is higher for more difficult tasks (which would require more attention) (Murthy and Fetz 1992; Kilner et al. 2000) and lower with elapsed time or, possibly, practice (Feige et al. 2000; Kilner et al. 2000) (which would require less attention), it is most likely that EEG-EMG coherence is primarily influenced by attention state.

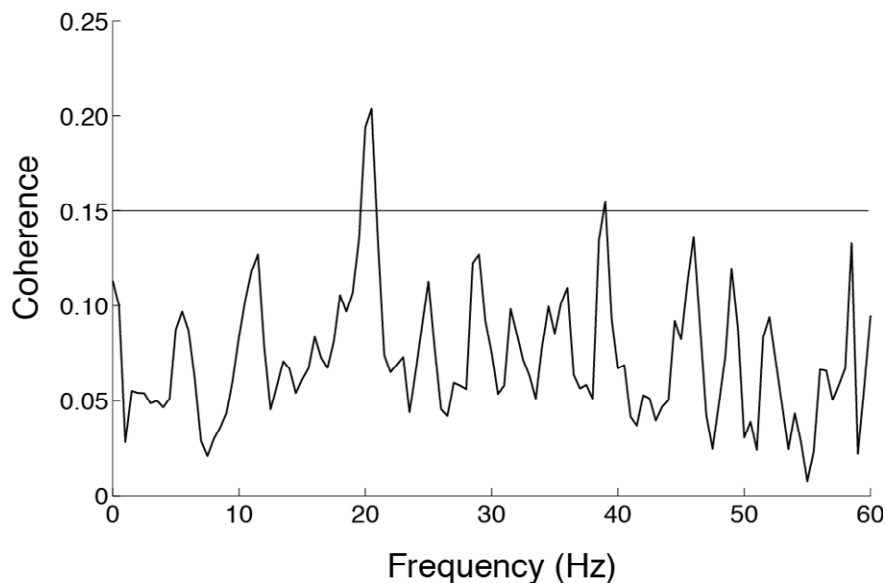


Figure 2. Example for EEG-EMG coherence (peak in 15-30 Hz range)

In fact, one study (Kristeva-Feige et al. 2002) has attempted to explore this possibility and reported supportive observations. However, their observations were unclear and ambiguous because of multiple confounding factors. Their study relied on subjects' intention in controlling the amount of attention and precision – the resolution of visual feedback was not changed between conditions. The contraction duration (2.5 min) was too long considering coherence reduces with time (Kilner et al. 2000) and attention state may fluctuate with time. Therefore, while their finding of a decrease of coherence in the “increased attention and precision” condition may indirectly infer the effects of attention on coherence, it remains uncertain if the decrease is due to the amount of attention or if the prolonged contraction duration influenced the results.

In our preliminary studies (Johnson et al. 2010, Johnson & Shinohara 2010), we have found that EEG-EMG coherence during a motor task is reduced with concurrent additional task that divided the attention of subjects from the main motor task. Those results were also supportive, but the experiments had different scientific purposes and thus did not test the influence of attention explicitly.

2. SPECIFIC AIM

We hypothesized that the amount of attention to a motor task can be assessed objectively from EEG-EMG coherence. The specific aim of the project was to test if EEG-EMG coherence during a motor task is influenced by the amount of required attention to the motor task in healthy young adults. This project is relevant to the research area of “8.4 Neurophysiology and Cognitive Neuroscience (8. Life Sciences)” in the Army Research Office.

3. RESEARCH DESIGN

Subjects

Fourteen young, healthy subjects (7 men and 7 women) with a mean age of 24.4 ± 4.6 years participated in the study. Each subject signed an informed consent approved by the Georgia Institute of Technology Institutional Review Board prior to participation in the study and in accordance with the 1964 Declaration of Helsinki. All of the subjects were right-handed as tested by the Edinburgh Handedness Inventory (Oldfield 1971) and met inclusion qualifications on an initial screening form. They did not have specific, hand muscle training, high or low blood pressure, any neurological disorder, arthritis in the hands, skin allergies, medications affecting motor control, or pregnancy. Each subject was tested for visual acuity using the Snellen Eye Chart to insure an ability to see the computer screen. Following set-up, subjects were also confirmed that they were able to see the computer screen without difficulty.

Experiment

Subject orientation:

In an electrically shielded room, subjects were placed in a seated position with both feet flat on the floor and the right arm resting comfortably in 45° of shoulder abduction and 90° of elbow flexion and forearm pronation. The middle, ring, and little fingers of the right hand were

restrained with a metal plate and Velcro strap. The thumb was restrained in a position $\sim 50^\circ$ from the index finger while in the same horizontal plane. The index finger was maintained with interphalangeal joints extended utilizing a trough splint that was attached to a task-dependent force transducer (Model 34 or Model 31, Honeywell, Ohio, USA) at the proximal interphalangeal joint during each trial.



Figure 3. Experimental setup in the preliminary study. EEG was recorded from the motor cortex (M1) and EMG was recorded from a hand muscle (first dorsal interosseus).

The splint was connected to the force transducer that was connected to an amplifier (Transbridge 4M, World Precision Instruments, Sarasota, Florida, USA). The index finger was maintained at a position level with the force transducer during each task and allowed to rest in flexion between tasks. The placement of the wrist and forearm was maintained with a vacuum foam pad so only the finger abduction force was applied to the force transducer. The left arm was free to rest comfortably on the subject's lap. Subjects were instructed to minimize any unnecessary movement such as blinking and to keep their heads straight throughout the trials.

EEG:

Electroencephalogram (EEG) recordings were made with the ActiveTwo Biosemi electrode system (Biosemi, Amsterdam, The Netherlands). This system is equipped with a miniature preamp adjacent to each electrode to reduce the contamination of the signal. To reduce the noise further, a battery powered A/D converter will digitize the recording and transfers it to a computer through a fiber optic connection. The international 10-20 electrode method for placement was used to obtain cortical EEG signals. Ground electrodes were placed on the scalp. Ag-AgCl pin electrodes were placed at C3, F3, and FC3A and referenced to Cz (Active Two, BioSemi, Amsterdam, Netherlands). Electrooculogram (EOG) electrodes (Ag-AgCl) were placed bilaterally, ~ 1 cm lateral to each eye as well as one between the eyebrows. Additional reference electrodes were placed at the bilateral earlobes. Set-up enabled eye blinks to be monitored in real time.

EMG:

Surface electromyogram (EMG) was recorded using the ActiveTwo Biosemi electrode system (Biosemi, Amsterdam, The Netherlands) in which preamps are attached to electrodes. Ag-AgCl

electrodes were placed on the skin over the right first dorsal interosseus muscle at the distal tendon and over the muscle belly. The reference electrode was placed at the ulnar styloid process. All electrodes were placed following a cleaning procedure to remove dead skin and oils from the skin surface to lower levels of impedance and improve the signal recorded.

Data recording and analysis:

EEG, EOG, and EMG signals were digitized on a computer with ActiView software (Biosemi, Amsterdam, The Netherlands) and sampled at 2048 samples/s. Force was recorded using Spike 2 software (Cambridge Electronic Design, Ltd., Cambridge, UK) after being amplified (Transbridge 4M, World Precision Instruments, Sarasota, Florida, USA). Force was digitized at 2048 samples/sec in parallel to bioelectrical data (Power 1401, Cambridge Electronic Design, Cambridge, UK). Data were synchronized between force and bioelectric signals using a synchronization pulse.

MVC task:

Subjects were asked to refrain from caffeine and nicotine use for the 2-3 hours prior to the experiment. Following set-up of the EEG, EOG, and EMG, the subjects were asked to perform the isometric MVCs with the first dorsal interosseus muscle of the right hand. The MVC was determined using a protocol described previously (Shinohara et al. 2005). The MVC task consisted of a gradual increase in force from zero to maximum over 3 s with the maximal force held for 2 to 3 s. The task was conducted by abducting the index finger and pulling on a rigid piece attached to the force transducer (21.3 N/V; Model 34, Honeywell, Ohio, USA). Subjects were verbally encouraged to achieve maximal force while the force was visually displayed on a monitor in front of the subject. Three to four trials were performed, excluding trials not within 5% of maximal force of each other. The highest peak force across trials was determined as MVC force.

Force matching tasks:

Following determination of the MVC, submaximal force matching tasks with various visual feedback conditions were performed. The target for each matching task was set for 5% MVC force. Onscreen visual feedback was displayed including a target force level and the actual force level exerted by the subject. To induce variability in subjects' attention, real-time onscreen visual feedback conditions were varied by changing the gain of force feedback (y-axis scaling) or removing the feedback. The visual feedback conditions included the feedback gain of low (FG1), moderately low (FG2), moderately high (FG3), high (FG4), and no feedback (FGN) (Figure 1). The FG1 task had y-axis scaling with the gain set lowest. The gain was progressively increased for the FG2, FG3, and FG4 tasks using the average standard deviation (SD) from three practice trials. The SD was added or subtracted along with a constant from the target value of 5% MVC force. For the FGN task, after 5 s of force matching with feedback scale consistent with the FG3 task, visual feedback was removed by turning off the computer screen.

The order of the force matching tasks was randomized. Each trial lasted 15 s for the sustained contraction. The trial was performed in blocks of 6 trials with a 30 s rest between trials and a 1-2 min rest between tasks. One practice was provided for each task prior to the trials. Prior to each trial, the subjects were instructed to match the target and to keep their eyes on the screen. The index finger splint was connected to the force transducer via a compliant spring (stiffness: 0.21

N/mm, mass: 0.24 g) (Johnson et al. 2010) because corticomuscular coherence is more evident with an addition of compliance in the transmission of force (Kilner et al. 2000). Data were recorded for force from the force transducer (9.2 N/V; Model 31, Honeywell, Ohio, USA). Trials with more than five eye blinks or speaking during the 15-second trial were excluded and subsequently repeated.

Following each task, the subjects reported their subjective perception of attention intensity required for the completed task using a 10-cm visual analog scale (VAS) that ranged from “no attention required” to “most attention required”. VAS data were measured in millimeters from the “no attention required” (“0”) end to quantify the level of perceived attention.

Data analysis

Time-series data were analyzed off-line using a custom-written Matlab (The Mathworks Inc., Lowell, MA) code. Steady state data from the last 10 seconds of each trial were used for analysis. All variables were averaged across all 6 trials for each task.

Coherence:

Coherence between left cortical EEG and right first dorsal interosseus EMG were calculated according to our previous study (Johnson et al. 2010). Coherence were calculated for each frequency bin of interest, f , as described in the following equation according to (Halliday et al. 1995):

$$Coh_{xy}(f) = |R_{xy}(f)|^2 = \frac{|P_{xy}(f)|^2}{P_{xx}(f)P_{yy}(f)} \quad (1)$$

where P_{xy} is the cross-power spectrum for the EEG signal (x) and the rectified EMG signal (and unrectified EMG) (y) at a given frequency bin (f) and P_{xx} and P_{yy} are the respective power spectrums for the EEG signal and EMG signal at the same frequency. Coherence is a real number between 0 and 1 that provides a summary measure of the amount of surface EMG and EEG that can be explained in each other (or that are correlated). The confidence interval of the coherence function was measured (Rosenberg et al. 1989) at the α quantile for L number of segments. This formula is given for coherence calculations that are based on the Fourier transform (Rosenberg et al. 1989).

$$cl(\alpha = 0.95) = 1 - (1 - \alpha)^{\frac{1}{(L-1)}} \quad (2)$$

where L is the signal duration minus the overlap, divided by the window length minus the overlap. Non-correlated activity at each frequency is considered to be below the confidence interval. Individual subject trial data was averaged across 0.5 Hz bins. Coherence was analyzed within the beta band (15-30 Hz) and considered significant if the magnitude was more than 95% confidence limit (Rosenberg et al. 1989) that was 0.153. Magnitudes of EEG peaks within the beta band above the significant level of coherence were noted and the number of peaks was counted. In addition, the areas above the confidence interval as well as the total area within the beta band were calculated in Matlab.

Comparison of corticomuscular coherence between feedback conditions was performed by finding the peak coherence within the beta band for each trial of each task. This approach allowed inclusion of small shifts in coherence location within the beta band for the varying tasks.

A custom Matlab program was used to find coherence peaks above the confidence interval within the beta band.

Force:

Force data were analyzed off-line with the Spike2 analysis system (Cambridge Electronic Design, Ltd., Cambridge, UK). Force signals were low pass filtered at 50 Hz and coefficient of variance (standard deviation/mean) of force was determined.

Statistical Analysis:

Statistical analysis was performed using PASWStatistics 18.0 (SPSS Inc., Chicago, IL, USA). The dependent variables were EEG-EMG coherence magnitude, number of peaks, area above the confidence interval, total area in the beta band, force coefficient of variance, and VAS. These dependent variables were compared within subjects relative to visual feedback condition (independent variable) using an analysis of variance (ANOVA) with repeated measures. Means were compared between groups using an ANOVA. Post-hoc analysis was performed using Tukey for pair-wise comparisons. An alpha level of 0.05 was chosen for all statistical tests. $P < 0.05$ or $P < 0.01$ was additionally noted where appropriate. Unless stated otherwise, the data are presented as mean \pm standard deviation in the text and tables and mean values in the figures.

4. RESULTS

In the total of 14 subjects, two subjects did not show a peak in coherence above the confidence interval within the beta band in any tasks. The other subjects had at least one peak above the confidence interval within the beta band in at least one of the tasks. When the highest value of coherence within beta band was averaged across all 14 subjects, whether or not it was above the confidence interval, there was an increasing trend of mean coherence from FG2, FG3, FG4, and FGN in this order (Figure 5). The frequency location of the highest-peak coherence was not influenced by feedback condition. On average, it ranged 21.3-23.2 Hz across feedback conditions (Table 1).

Table 1. Frequency location of the highest-peak coherence in each feedback condition.

	FG1	FG2	FG3	FG4	FGN
All Subjects	22.0 \pm 4.8	21.3 \pm 4.2	22.9 \pm 4.6	21.9 \pm 4.4	23.2 \pm 3.6
7 Subjects	19.9 \pm 3.8	19.6 \pm 3.6	21.4 \pm 3.5	21.2 \pm 4.0	22.3 \pm 3.1

First row: data from all 14 subjects. Second row: data from 7 subjects who showed significant coherence above the confidence interval in FGN.

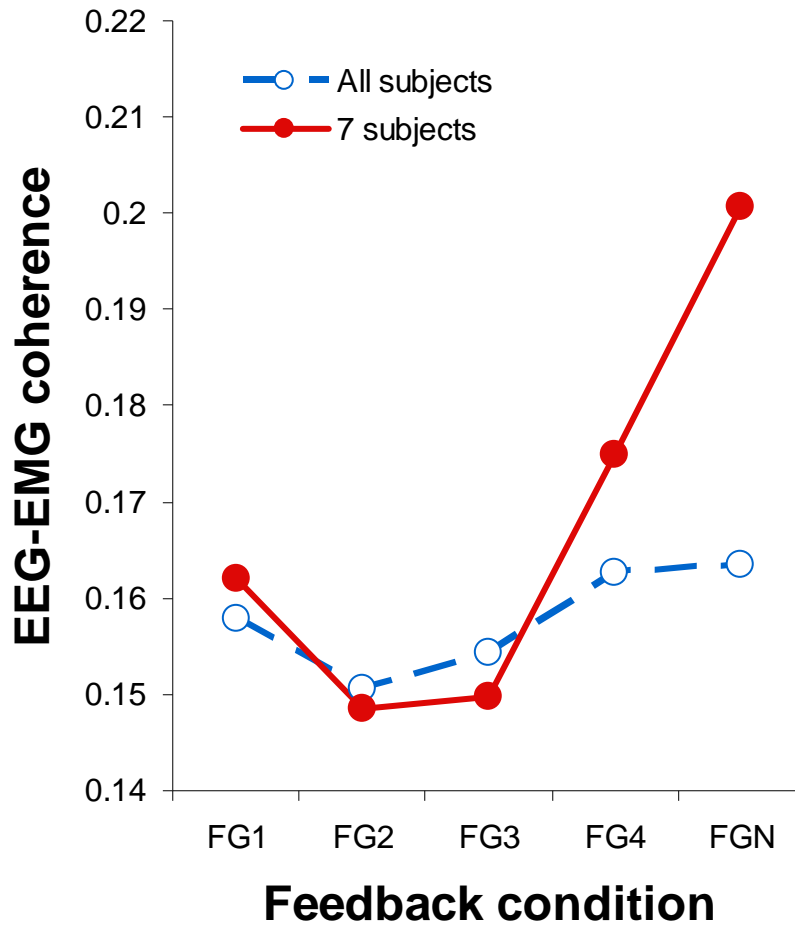


Figure 5. Beta band EEG-EMG coherence across feedback conditions. Open symbols with a broken line: values averaged across all subjects. Closed symbols with a solid line: values averaged across 7 subjects who showed significant coherence above the confidence interval in FGN. See text for details.

The number of subjects who demonstrated coherence above the confidence interval was greatest during the FGN task ($n = 7$). Data from these subjects were further analyzed for statistical comparisons of coherence. The magnitude of coherence was influenced by visual feedback, as supported by the significant main effect of feedback with repeated measures ANOVA ($p < 0.01$). Specifically, coherence for FGN was greater compared with FG1 ($p < 0.05$), FG2 ($p < 0.05$), and FG3 ($p < 0.05$). In addition, coherence for FG4 was greater compared with FG3 ($p < 0.05$). Coherence for FG 4 tended to be greater compared with FG2 and the difference did not reach statistical significance ($p = 0.054$). The frequency location of the highest-peak coherence for these subjects was not influenced by feedback condition. On average, it ranged 19.6-22.3 Hz across feedback conditions (Table 1).

According to the VAS score, subjects rated higher gain feedback tasks as requiring more attention compared with lower gain feedback tasks (Figure 6). This influence of feedback was confirmed by a significant main effect of feedback ($p < 0.01$) on VAS when all subjects were

analyzed together with repeated measures ANOVA. Pairwise comparison revealed that the VAS score in FG4 was higher compared with FG1, FG2, and FG3 ($p < 0.05$). The VAS score in FG3 was higher compared with FG1 and FG2 ($p < 0.05$). Similarly, when the seven subjects showing coherence above the confidence interval in the FGN task were analyzed with repeated measures ANOVA, there was a significant main effect of feedback ($p < 0.01$) on VAS. Pairwise comparison revealed that the VAS score in FG2, FG3, and FG4 were higher compared with FG1 ($p < 0.05$), and the VAS score in FG3 and FG4 were higher compared with FG2 ($p < 0.05$).

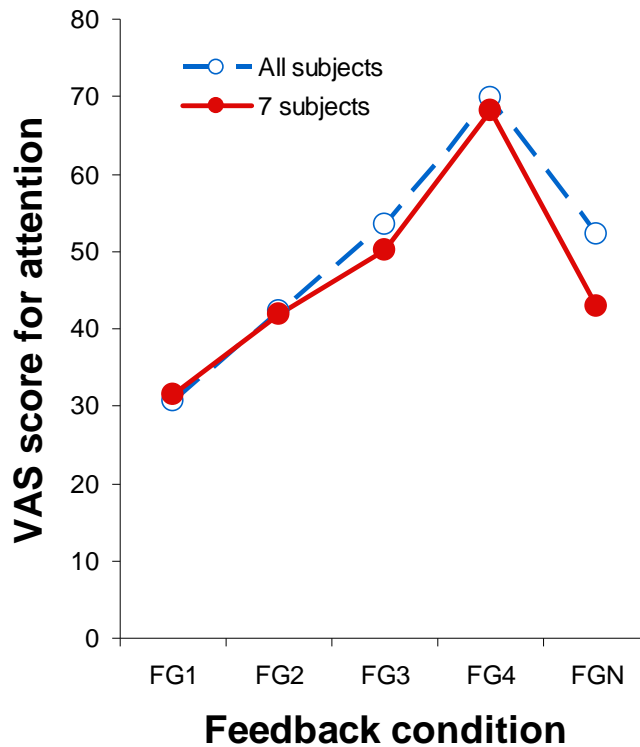


Figure 6. Visual analog scale (VAS) score for attention across feedback conditions. Open symbols with a broken line: VAS scores averaged across all subjects. Closed symbols with a solid line: VAS scores averaged across 7 subjects who showed significant coherence above the confidence interval in FGN. See text for details.

Fluctuations in force were examined with the coefficient of variation in force (Figure 7). When the coefficient of variation of force was analyzed with repeated measures ANOVA, Huynh-Feldt values were used for main effect since sphericity was violated. As a result, a significant main effect of feedback condition was present ($p < 0.05$). Following the pairwise comparisons, the coefficient of variation of force in FG4 was greater compared with FG2 and FG3 ($p < 0.05$). Similarly, the coefficient of variation of force in FGN was greater compared with FG2 and FG3 ($p < 0.05$). In addition, the coefficient of variation of force in FG1 was greater compared with FG2, FG3, and FGN ($p < 0.01$). There was no significant difference in the coefficient of variation of force between FG1 and FG4.

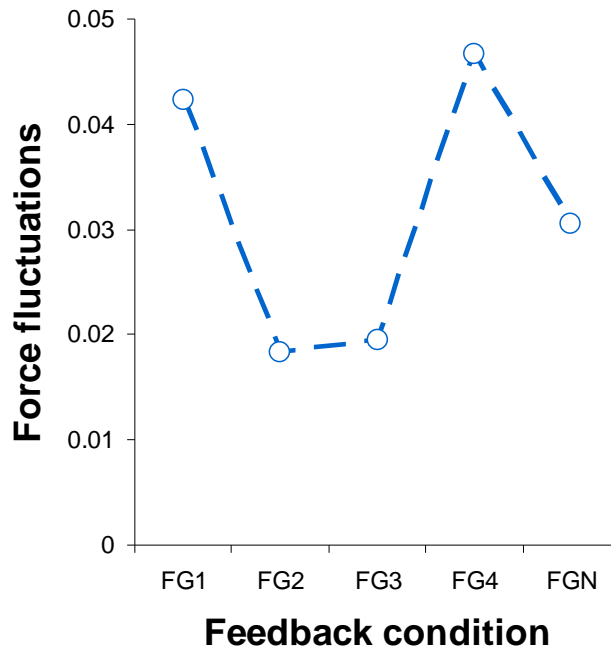


Figure 7. Force fluctuations (coefficient of variation of force) across feedback conditions. See text for details

When EEG-EMG coherence magnitudes were reviewed with respect to the VAS score and force, these values were not correlated significantly. There may be a slight tendency for higher coherence levels within the mid-range of VAS ratings when all ratings are viewed with respect to the coherence levels (Figure 8). With an average force coefficient of variation of 0.0315 ± 0.0261 across all trials, values for the force coefficient of variation did not vary according to EEG-EMG coherence magnitudes (Figure 9). There was no correlation between force fluctuations and VAS score, either (Figure 10).

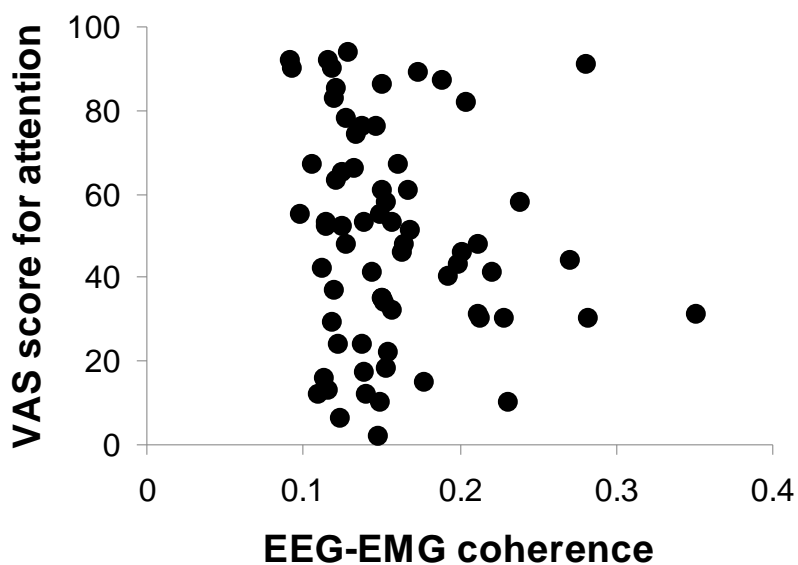


Figure 8. Scatter plots between EEG-EMG coherence and subjective perception of attention across individual subjects and conditions. There was no significant correlation.

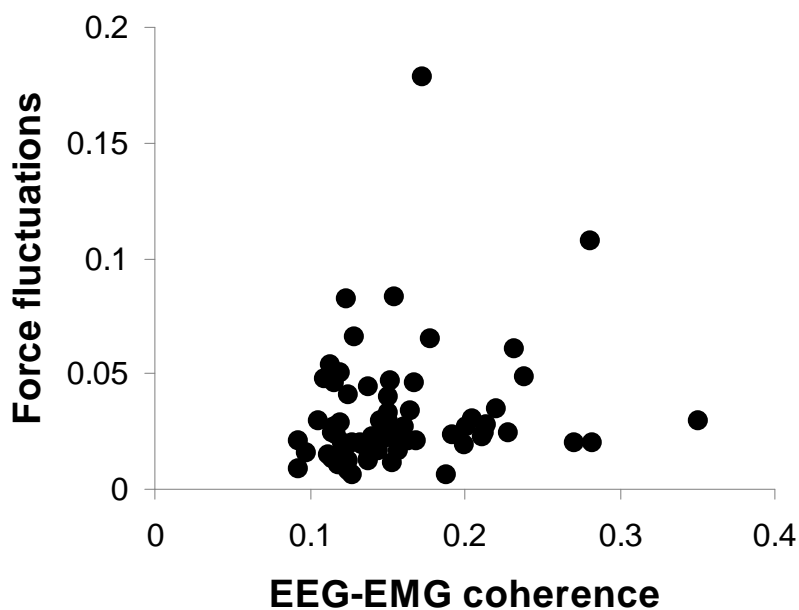


Figure 9. Scatter plots between EEG-EMG coherence and force fluctuations (coefficient of variation of force) across individual subjects and conditions. There was no significant correlation.

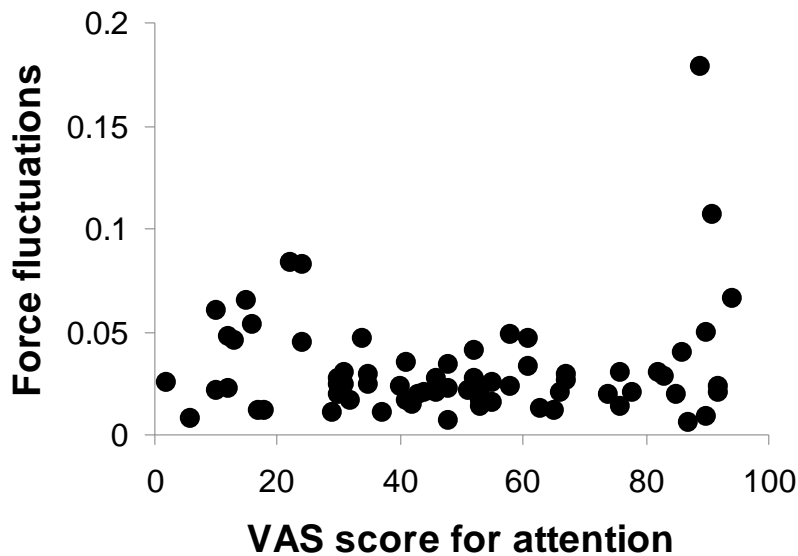


Figure 10. Scatter plots between VAS score for attention and force fluctuations (coefficient of variation of force) across individual subjects and conditions. There was no significant correlation.

5. DISCUSSION

The main findings were that 1) beta-band EEG-EMG coherence increased with increases in the visual feedback gain; 2) beta-band EEG-EMG coherence was greatest when subjects paid attention to the task without receiving visual feedback of their performance; and 3) there was no significant correlation between the subjective perception of attention intensity (VAS score) and beta-band EEG-EMG coherence in the individual data.

Visual feedback condition and EEG-EMG coherence

The increases in EEG-EMG coherence with the increases in the visual feedback gain supported our hypothesis, at least in part, that the amount of attention to a motor task can be assessed objectively from EEG-EMG coherence. During a steady force-matching task, more attention is required with greater visual feedback gain. In the current study, the visual feedback gain was varied across four levels (FG1-FG4). On average, EEG-EMG coherence was lowest with relatively small visual feedback gain (FG2), and it increased with an increase in the gain (Figure 6). This order was the same if data were averaged across all subjects or just seven subjects who showed significant EEG-EMG coherence, although the trend was more obvious in the latter. These results with objective manipulation of subject attention were in line with a previous study that asked subjects to vary their amount of attention subjectively (Kristeva-Feige et al. 2002). The findings were expected from our preliminary studies described above (Johnson et al. 2010, Johnson & Shinohara 2010) and from previous reports that depicted increased synchronized discharges in motor neurons with high-gain visual feedback (*e.g.* (Schmied et al. 2000)). The reduction in

The increase in EEG-EMG coherence from FG2 to FG3 was small probably because the visual feedback gain was increased linearly whereas the scaling in human perception/responses is often

non-linear. In other words, it is likely that the increase in the required amount of attention from FG2 to FG3 was smaller compared with that from FG3 to FG4. This speculation would be supported similar values in force fluctuations between FG2 and FG3 and greater force fluctuations in FG4 compared with FG3 (Figure 7).

The highest EEG-EMG coherence during the task without visual feedback (Figure 6) was as expected from our hypothesis. Without visual feedback information, subjects were required to pay close attention to the force perception in the contracting muscle. The finding indicated that EEG-EMG coherence was highest when subjects were required to pay most attention to the task. The reduction in EEG-EMG coherence from FG1 to FG2, although not statistically significant, was unexpected. However, this tendency may actually be explained from the opposite direction - as an increase in EEG-EMG coherence from FG2 to FG1 with a reduction in the quality of visual feedback information due to decreased visual feedback gain. In the FG1 condition, the visual feedback gain was so small that force fluctuations were not visible at all. Although the instruction to the subjects was to match the force target steadily, subjects received little information about their force fluctuations. To compensate for the reduced amount of feedback information, it is likely that subjects unconsciously paid attention to the contracting muscle for steady force production.

Subjective perception of attention intensity and EEG-EMG coherence

When the perception of attention intensity to the task was subjectively reported with the VAS, the VAS score increased with visual feedback gain from FG1 to FG4 (Figure 6). As much as the objective quantification of attention status is very difficult, the distinction of perceived attention status is very difficult. The VAS is a subjective assessment tool that is often employed in psychological studies. Although subjects were instructed to report their amount of attention to the task, it is unclear if subjects were able to scale it reliably. This interpretation is supported by the fact that the VAS score in the FGN condition (that requires most attention) was lower compared with the FG3 and FG4 conditions. It is of note that the FGN condition was preceded by force matching with visual feedback that corresponded to the FG3 condition. Therefore, it is likely that, with the VAS, subjects reported the difficulty of the task based on the visual feedback gain.

In this line, the absence of significant correlation between the VAS score and EEG-EMG coherence across individuals and conditions would indicate that the subjective assessment of attention status and objective value of EEG-EMG coherence were not correlated. Based on the current findings and previous reports that support the influence of attention status on EEG-EMG coherence (Johnson et al. 2010, Johnson & Shinohara 2010, Kristeva-Feige et al. 2002), it would be interpreted that beta band EEG-EMG coherence has a potential for objectively detecting the attention status that may not be detected from subjective reports.

Fine motor performance and EEG-EMG coherence

When the amount of force fluctuations was assessed as an index of fine motor performance during the steady contraction, it varied depending on the visual feedback condition (Figure 7). On average, force fluctuations were smallest in the FG2 and FG3 conditions, and increased with a greater visual feedback gain in the FG4 conditions. Force fluctuations in the FG4 condition was even greater compared with FGN (no feedback) condition. Although greater force

fluctuations with greater visual feedback gain may seem counter-intuitive, similar findings have been found previously. With increased amount of visual feedback information, individuals attend more to the task. This leads to greater and more frequent intentional force corrections (*i.e.* excessive visuomotor correction), resulting in greater fluctuations (Tracy 2007). In this way, the influence of visual feedback condition or attention on the amount of force fluctuations is not straightforward. In addition, no correlation was found in our previous studies (Johnson et al. 2010, Johnson & Shinohara 2010) between force fluctuations and EEG-EMG coherence. Hence, it is not surprising that there was no correlation between force fluctuations and EEG-EMG coherence (Figure 9).

Future directions

The current results showing the greater beta-band EEG-EMG coherence with increased visual feedback gain supported that correlated oscillations in brain and muscle in the beta band have a potential for objectively detecting the attention status that may not be detected from subjective reports. The current findings are the basis for the future applicability of this technique for objectively assessing the attention state of individual war-fighters under different conditions. If not in the battlefield, EEG-EMG coherence in the laboratory setting would help identify specific conditions that influence the attention state depending on the individual. In addition, the specific battlefield conditions that would distract attention state may also be identified in further studies with this technique.

Sine this project was supported as a short-term project, the study design was limited to the low-intensity contraction of a hand muscle in healthy young adults. Recent studies demonstrated that EEG-EMG coherence is influenced by many factors such as involved muscle, training status of the tested individuals, contraction intensity, and muscle fatigue (Chakarov et al. 2009; Ushiyama et al. 2010; Yang et al. 2009). Future studies are warranted that will extend the current findings to other muscles, task conditions, and subject populations.

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